INDIA-SPAIN WORKSHOP ON RENEWABLE ENERGIES

Silicon Technology for Photovoltaics

POLITÉCNICA
Instituto de Energía Solar

Carlos del Cañizo
Director
INSTITUTO DE ENERGÍA SOLAR

Sevilla, March 2nd, 2011

The Instituto de Energía Solar

Founded by Antonio Luque in 1979

Personnel: 64 full-time staff (19 professors, 4 PhD researchers, 28 PhD students, 13 administrative and maintenance staff), 19 “part time” (11 “external PhD students”, 8 master students)

Objective: Contribute to the deployment of Photovoltaic Solar Electricity through R&D&i

Programs:

- Photovoltaic Systems
- Systems and Instr. Integr.
- Silicon Technology
- Fundamental Studies
- III-V Semiconductors

Project funding from: Public Funds (81.7%) [[European Union (16.9%), National Government (60.4%) Regional Governments (4.4%]], private companies (18.3%).

Photovoltaic Systems Program

Objective: the study of the specific problems associated with the engineering of photovoltaic systems, both off- and on-grid. Special emphasis is paid to the aspects relative to the control of the technical quality by means of easily reproduced procedures.

It supports the manufacturing industry of Photovoltaic equipment, and has played a prominent role in the Spanish market of solar farms.

System and Instruments Integration Program

Objective: the development of equipment, instruments and methods for the measurement and characterization of solar cells collectors, CPV systems and plants both in the laboratory and in the open air.

Likewise, it is involved in the development of prototypes, new concentration systems and concepts, even larger plants derived from these in collaboration with, on very many occasions, companies and/or other public institutions.

SOLAR SIMULATORS
COMMERCIALLY AVAILABLE

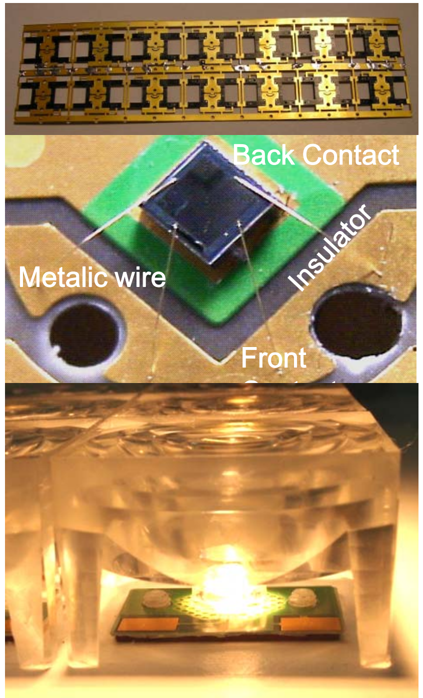
IES spin-off: ISFOC

According to a plan of the IES-UPM, a new Institute for CPV Systems (ISFOC) has been created in Spain (25 M€ + 0.9M€/year) that has issued two international calls for tenders; 3 MWp have been granted to Solfocus (US), Concentrix (DE), Isofotón (ES), Sol3G (ES), Arima (TW), Encore (US) and CSLM (ES)

III-V Semiconductors Program

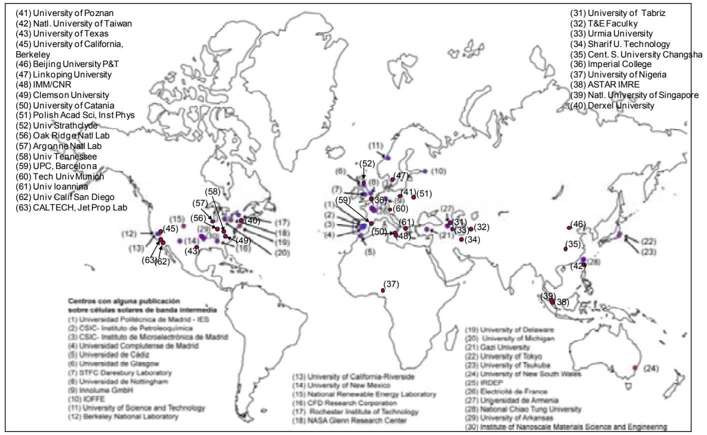
Objective: the research on solar cells based on III-V semiconductors and which can operate efficiently under very high light concentrations (> 1000 suns).
The field of interest include the theory, design, technology, manufacturing and characterization of the devices and the systems that incorporate them. In all cases the possibility of transferring the results to industry is a goal and thus costs analysis and reliability analysis are carried out.

NEW WORLDWIDE RECORD IN 2J Solar Cells!!!
32.6% at 1000X

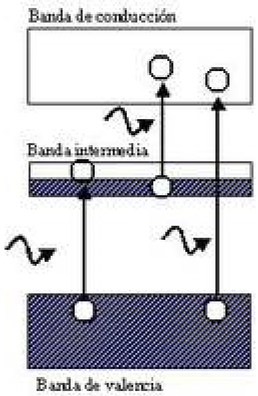


Fundamental Studies Program

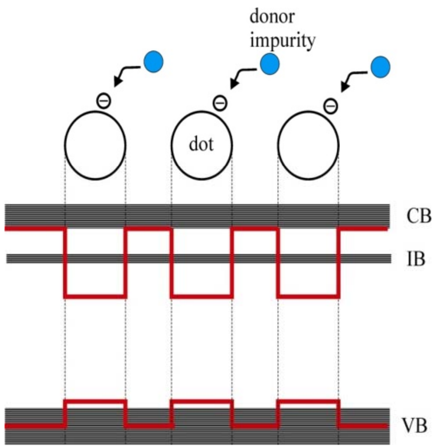
Objective: to study the conversion limits when converting solar energy into electricity, and identify mechanisms which could drastically improve the present performance of this conversion.
Also, its activity is focused on Quantum Mechanic band diagrams and optoelectronic properties of photovoltaic materials, using concepts of quantum chemistry and solid state physics.

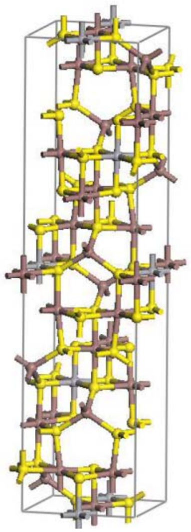


"Inspiring" research of more than 60 laboratories worldwide



Schematic representation of an intermediate band material

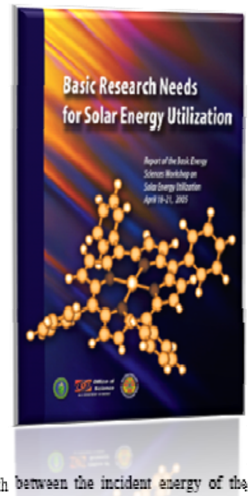




Practical implementation of an intermediate band material by quantum dots and In_2S_3:V

DOE-USA:

Revolutionary Photovoltaic Devices: 50% Efficient Solar Cells



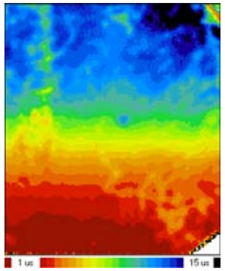
Multiple Energy Level Solar Cells

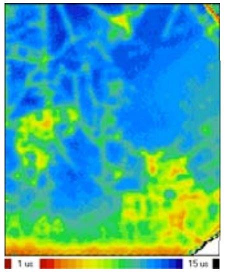
In multiple energy level solar cells, the mismatch between the incident energy of the solar spectrum and a single band gap is accommodated by introducing additional energy levels such that photons of different energies can be efficiently absorbed. Multiple energy level solar cells can be implemented either as localized energy levels (first suggested as a quantum well solar cell) or as continuous mini-bands (also called intermediate band for the first solar cell to suggest this approach) (Marti and Luque 2003; Green 2004). Both cases, which are shown in Figure 23, have a fundamental similarity in that the key issue is the generation of multiple light-generated energy levels for electrons.

Silicon Technology Program

Objective: to give support to crystalline silicon solar cell industries, which make up the majority of those present in the market.

In order to help them to reduce costs as well as develop new products, it covers both solar cell processing and material related issues.

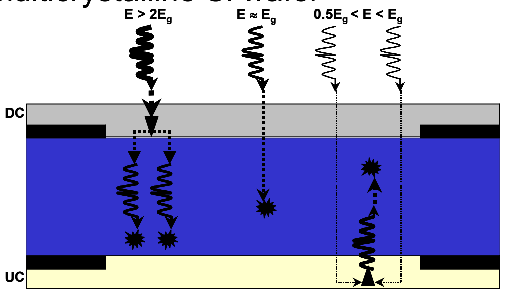




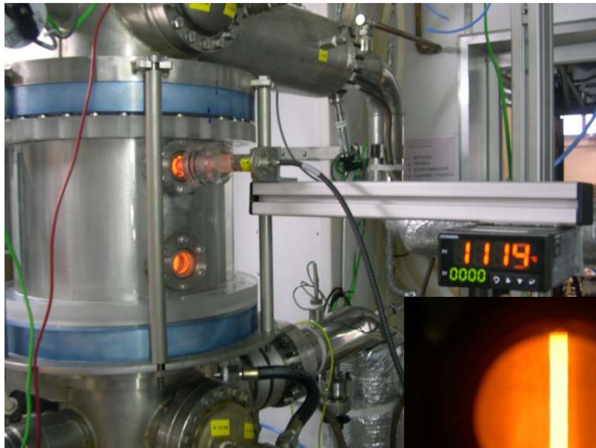
$\tau_i = 10\ \mu s$
$[Fe_i]_i = 1.10^{12}\ cm^{-3}$

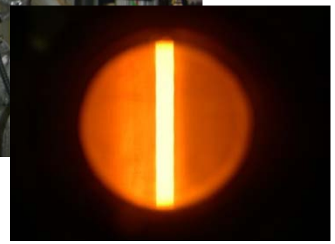
$\tau_f = 12\ \mu s$
$[Fe_i]_f \leq 5.10^{10}\ cm^{-3}$

Influence of a slow cooling step in the quality of a multicrystalline Si wafer



Applying up-converters to a bifacial solar cell

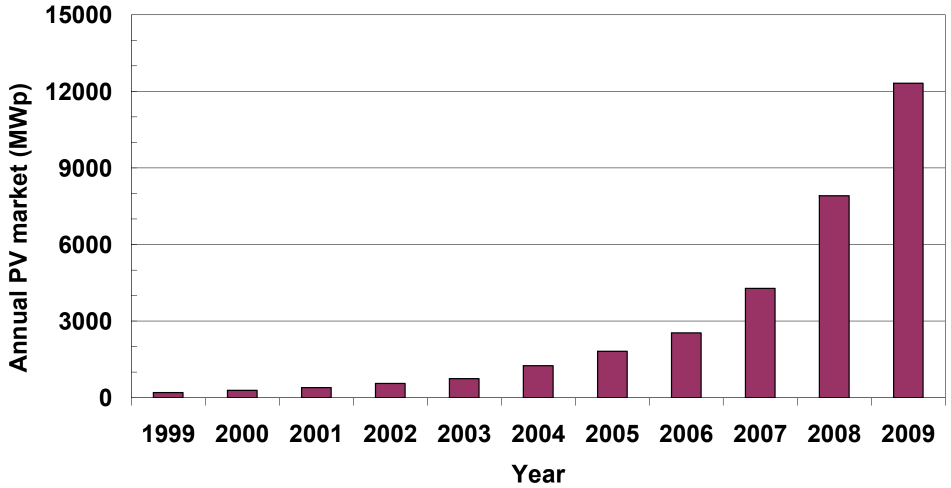


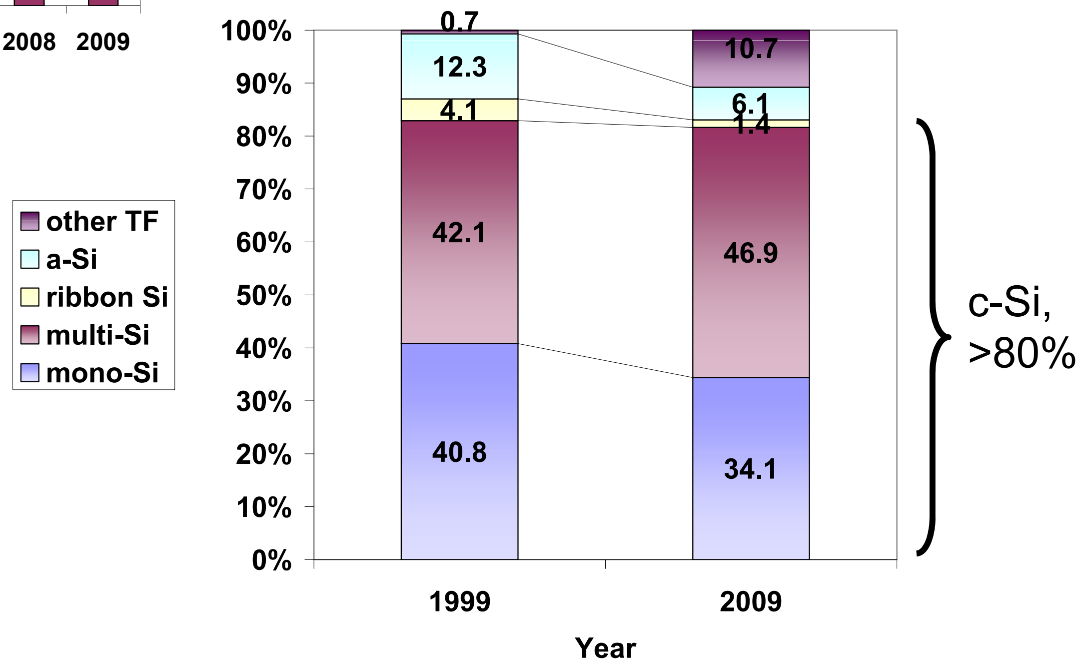


CVD reactor prototype

CENTESIL
Centro de tecnología del silicio solar

Silicon for Photovoltaics





Photon International, 3/2010

Strength of Silicon for Photovoltaics

- ✓Workhorse of PV since its early days
- ✓It has already provided around 20 GWp (accumulated production)
- ✓The technology and raw materials are there to provide 100 GWp/a or higher
- ✓Price has reduced 60% in the last 10 years, even when the silicon shortage was experienced

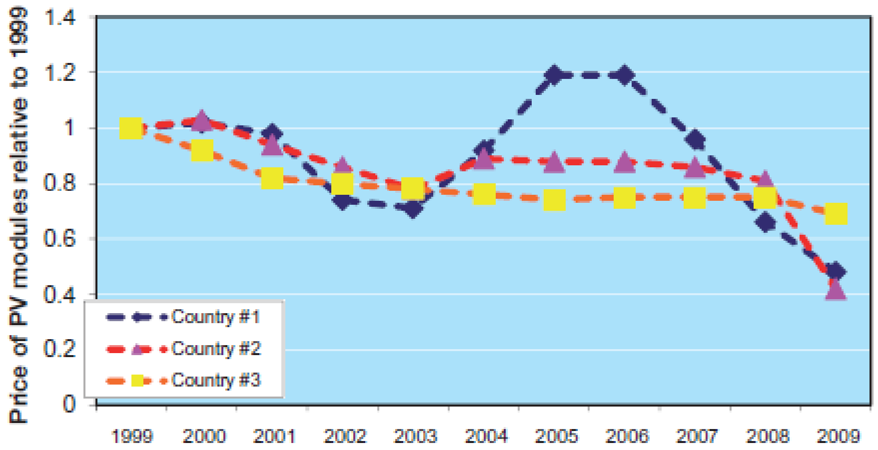


Figure 9 – Evolution of price of PV modules in selected reporting countries accounting for inflation effects – Years 1999–2009 (Normalized to 1999)

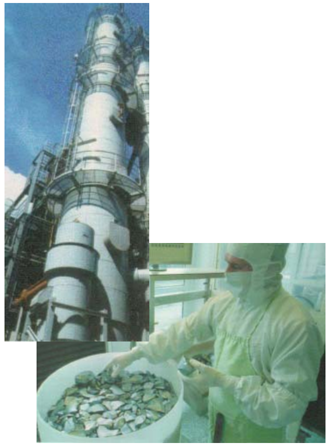
Source: Agencia Internacional de la Energía. Informe: Trends in Photovoltaic Applications, August 2010.

The Si value chain: from silica to systems

quartz →
carbon →

Reduction to metallurgical Si

→

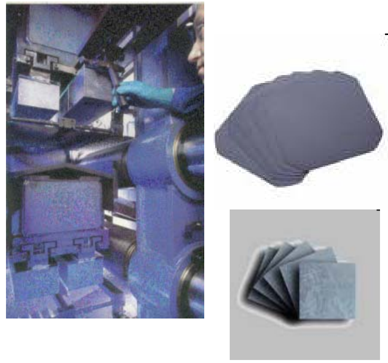


Ultrapurification to polysilicon

→

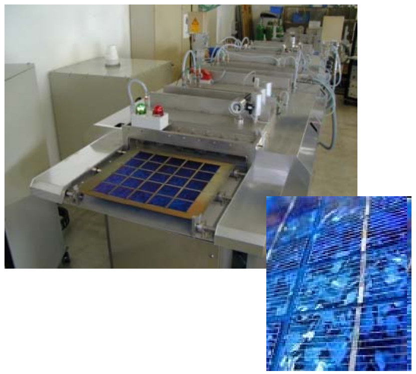
Crystallisation

→



Wafering

→



Solar cell processing

→

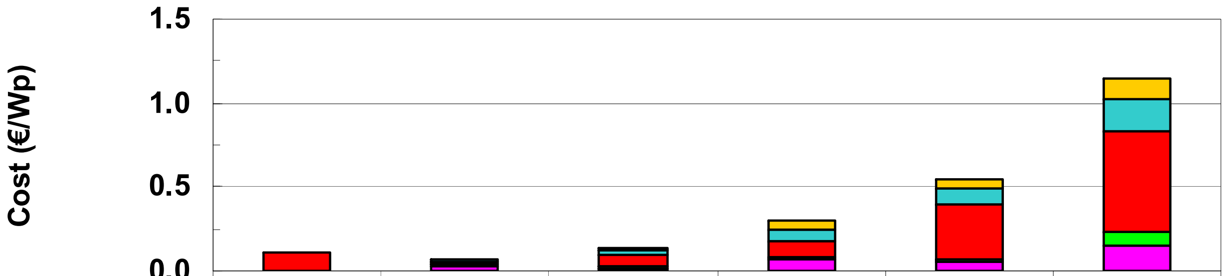
Module assembly

→

System implementation

Cost analysis of PV c-Si technology

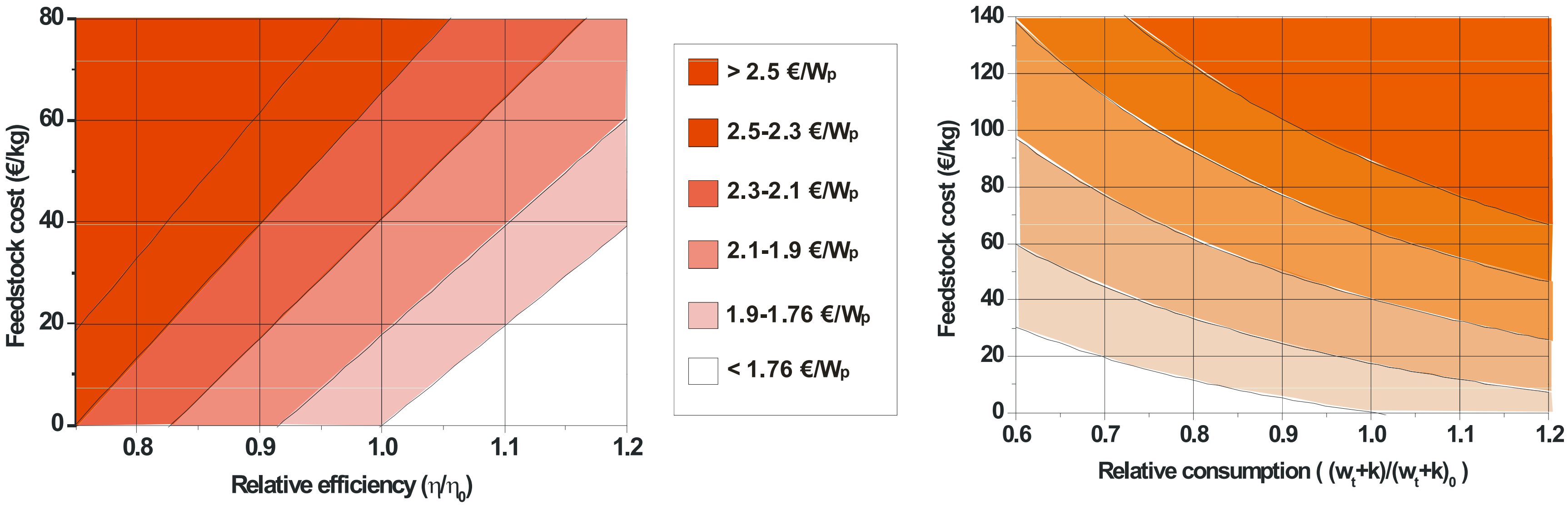
- Work performed within CrystalClear project (EU, 6th FP)
- Reference technology (Advanced Basepower)
  - Feedstock at 20 €/kg
  - mc-Si, 180 μm thick, 170 μm kerf loss
  - 15.8% encapsulated cell efficiency
  - Standard processing (screenprinting, Al BSF, soldering, foil lamination…)
  - Large scale production (~ 300 MWp/a)



	Feedstock	Ingot Growth	Wafering	Cell processing	Module Assembly	Total
Equipment		0.01	0.01	0.06	0.04	0.13
Labour		0.01	0.02	0.06	0.10	0.19
Material	0.10	0.02	0.06	0.10	0.33	0.61
Yield losses		0.01	0.02	0.02	0.02	0.08
Fixed		0.02	0.01	0.06	0.05	0.15
Total	0.10	0.07	0.13	0.30	0.54	1.15

Sensitivity analysis for main cost drivers

- **Analysis the impact of relevant factors on cost: feedstock cost and yield, material loss in crystallisation, slicing pitch (wafer thickness + kerf loss), encapsulated cell efficiency**



- **Reduction in Si feedstock cost by 55% reduces total module cost by 6%**
- **Reduction in slicing pitch by 25% reduces total module cost by 7%**
- **Increase in encapsulated cell efficiency by 8% reduces total module cost by 8%**

Some technological challenges on Silicon PV

- Polisilicon below 30 €/kg compatible with cell efficiencies in the range of 20%. Polisilicon below 10 €/kg compatible with cell efficiencies in the range of 15%.
- High quality crystals, with low impurity and defect concentration from high throughput crystallisation processes
- Very thin wafers, below 80 μm, with kerf losses in the range of 100 μm
- Cell technologies giving efficiencies over 20% for very thin wafers, with a silicon usage below 2.5 g/Wp
- Long life (over 35 years) encapsulation techniques compatible with very thin cells. Encapsulation of rear contacted solar cells

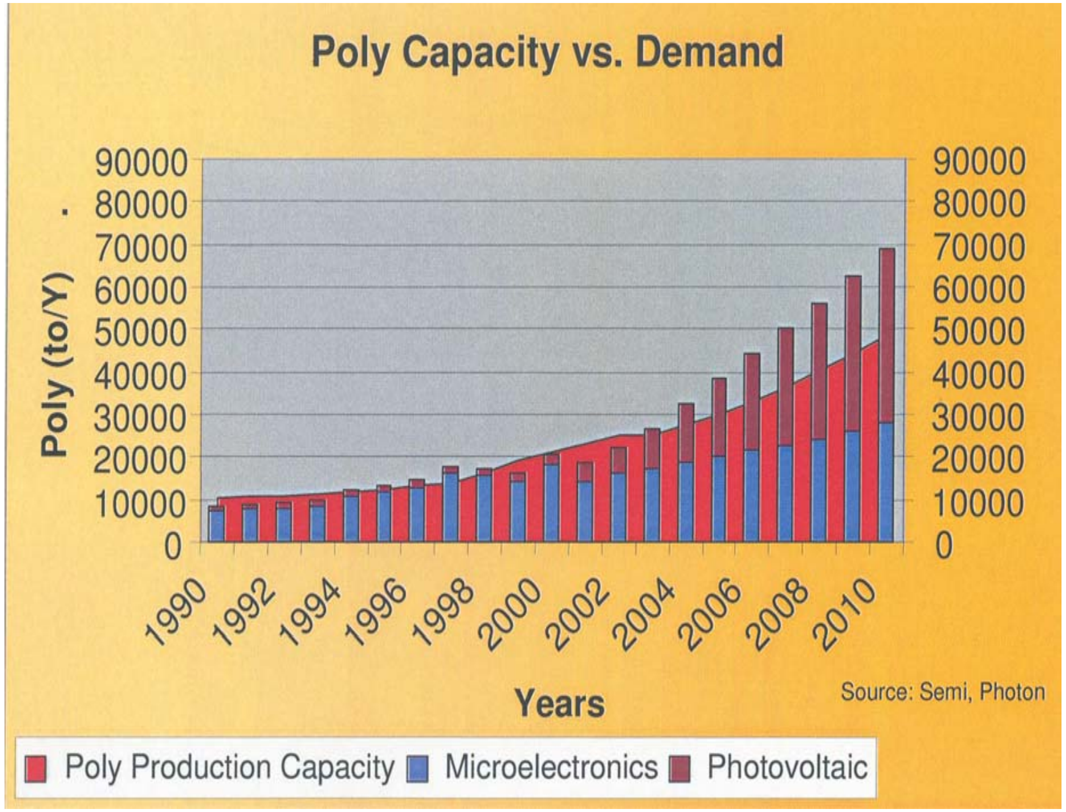
The PV Spanish sector

ASIF, annual report 2010

- The whole silicon PV value chain covered in Spain
- Internationally recognised R&D infrastructure

The revolution in the Si feedstock market

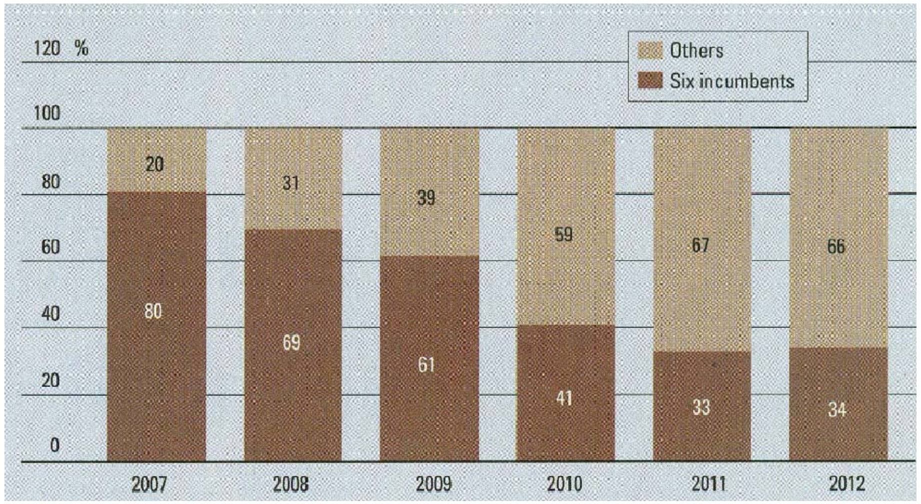
P. Fath, A. Mozer, 3rd Solar Si Conf, 2006



- 2006-2007: Silicon shortage
  - Slow reaction of polysilicon producers to expand capacity
  - New entrants trying to acquire the technology
  - Intensive R&D on polysilicon purification for solar

The revolution in the Si feedstock market (2)

- **2009: Quick change of scenario towards oversupply**
  - New capacity installed in a context of market slow-down
  - Pressure on new entrants, that need to demonstrate good material quality and low costs



M. Rogol, Photon Int, 7/2009

- **In the medium and long run:**
  - PolySi production structure changing to a "distributed" one: ~2000 t of Si for a 300 MWp PV plant
  - Technology changes when targeting "Solar Silicon"

Acceptable concentration of contaminants in Si

Ti Cr Fe Cu

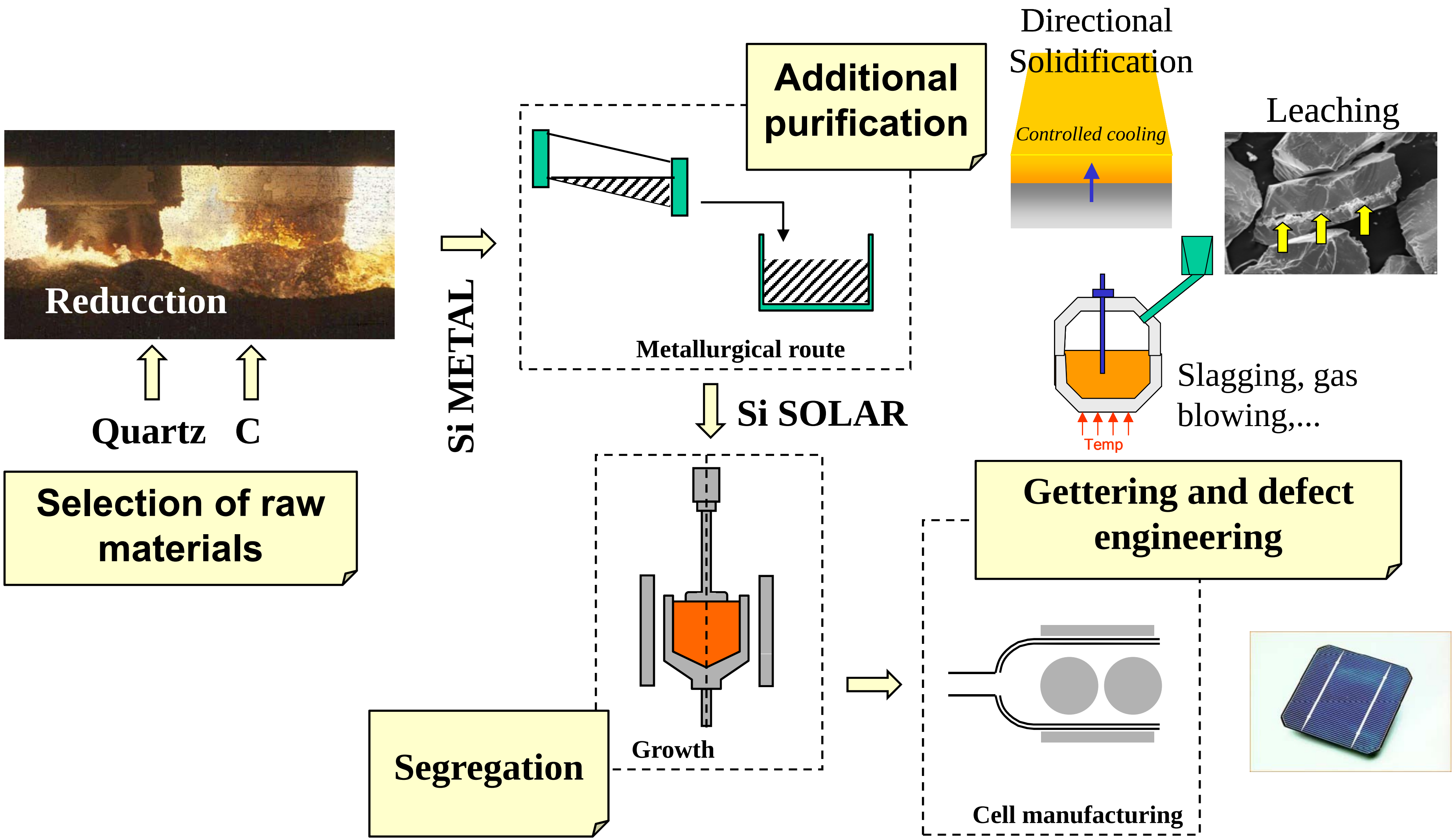
Slow → **Quick**
+Harmful → ***-Harmful***

Element	*Reference for semiconductor polysilicon [ppma]*	*Concentration in the polysilicon for a monocrystalline solar cell [ppma]*	*Concentration in the polysilicon for a multicrystalline solar cell [ppma]*
Ti	< 0.003	0.0002	0.022
Cr	< 0.003	0.18	0.026
Fe	< 0.01	9.4	12.5
Cu	< 0.003	8.4	4.6

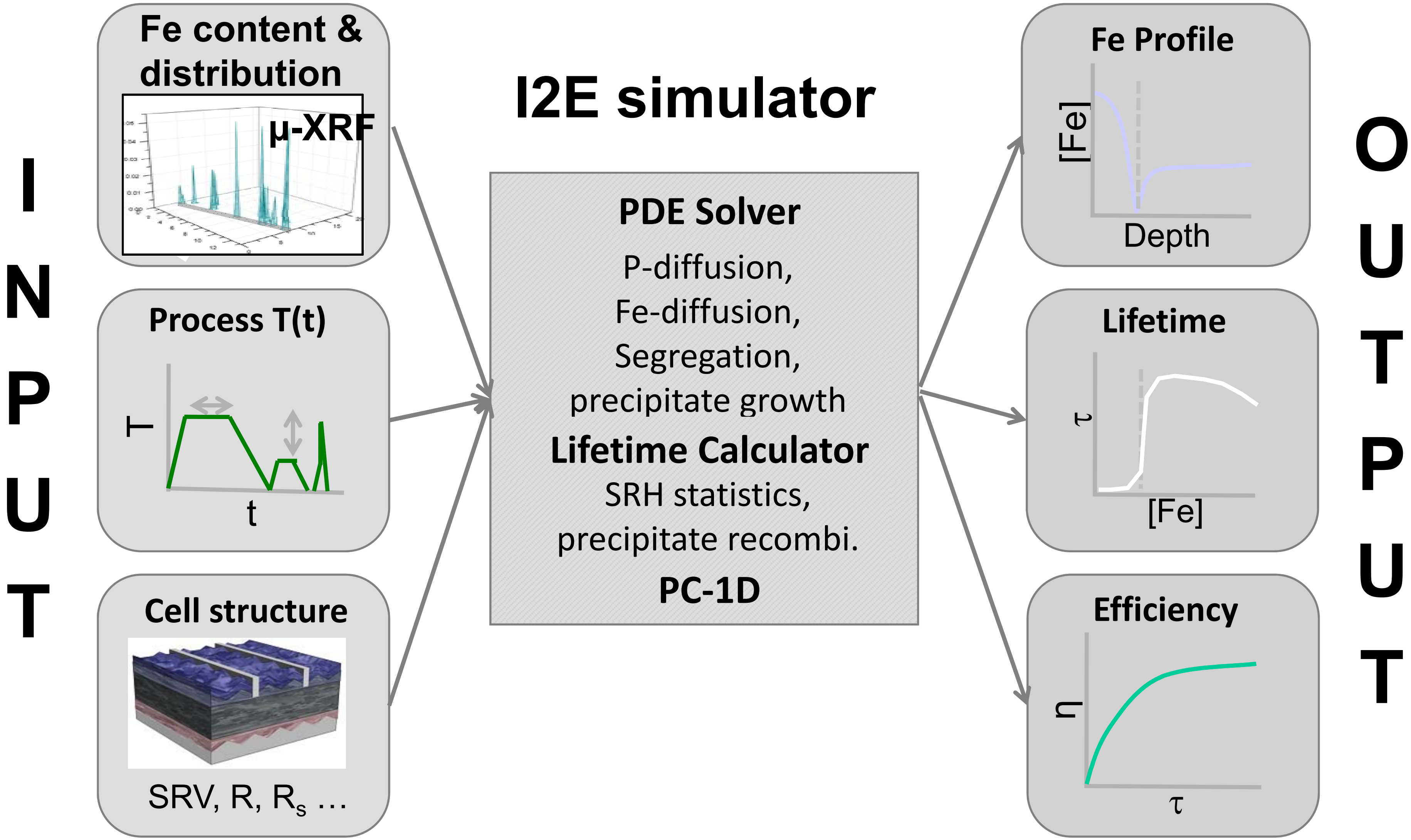
C. del Cañizo et al, 20th European PVSEC (2005)
J. Hofstetter et al, Mat Scien & Eng B, 159-160 (2009)

- **Solar Silicon purity, less strict than that of electronic grade Si**
- **Purification methods should consider dedicated steps for specific impurities**
- **Acceptable contamination level also depends on the crystallisation method**

Polysilicon purification via metallurgical route



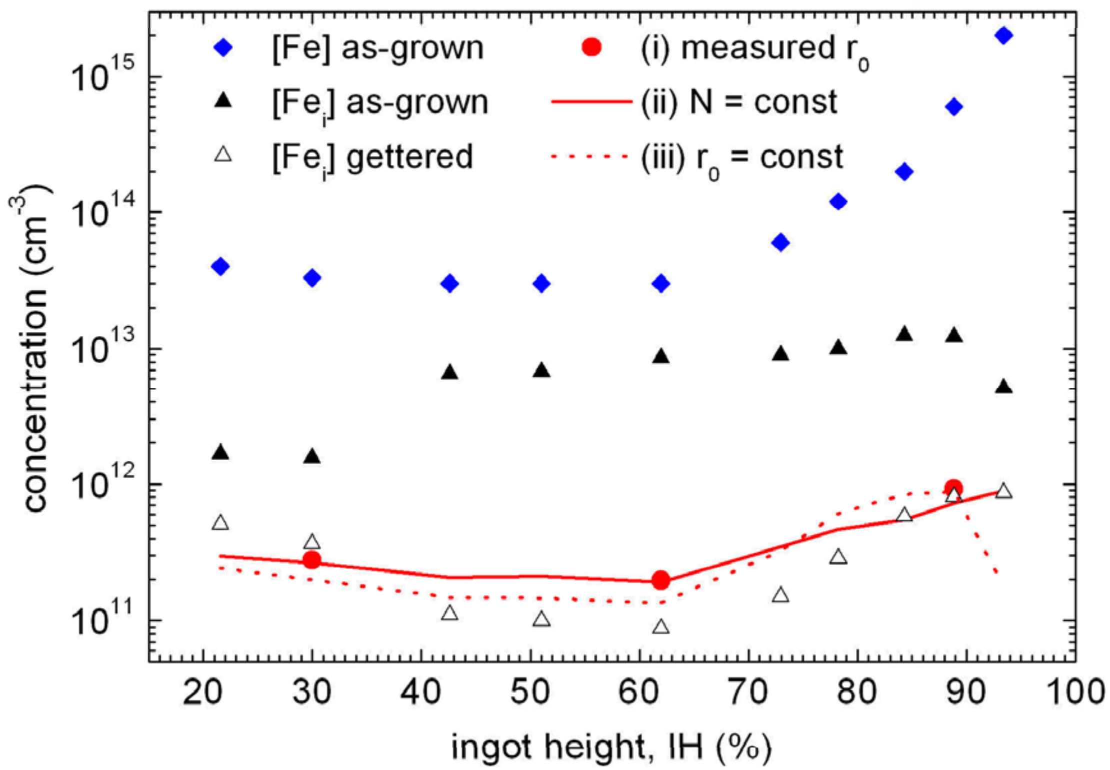
Impurities-to-Efficiency Model: I2E



A collaboration between IES-UPM and MIT

I2E Model validation: Fe distribution

Fe distribution along mc-Si ingot grown from **intentionally Fe-contaminated feedstock**



Hofstetter *et al.* Progress in Photovoltaics, accepted for publication (2010)
Coletti *et al.* J. of Applied Physics (2008) vol. 104 (10) pp. 104913

I2E **input parameters** along IH:

- ◆ total as-grown [Fe]
- ▲ as-grown interstitial [Fe$_i$]

T(t) profile for P diffusion

△ interstitial [Fe$_i$] after PDG

→ **Final [Fe$_i$]** strongly depends on **as-grown [Fe]** and the **Fe distribution**

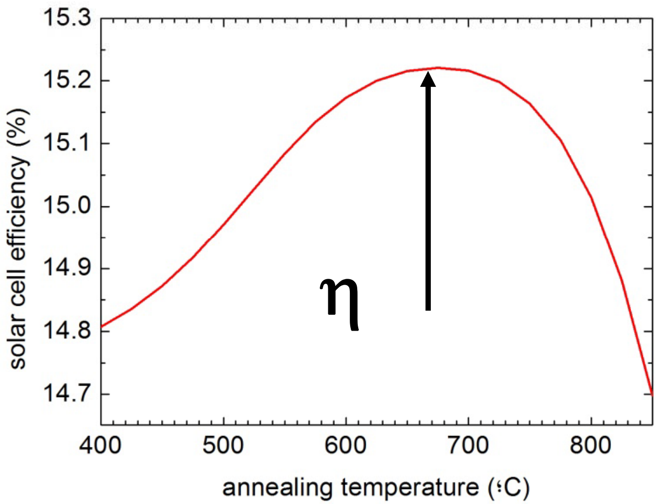
Application: Optimizing short LTA after PDG for industrial solar cell processing

Simulation:

10 min PDG at 900ºC + LTA varying T and t

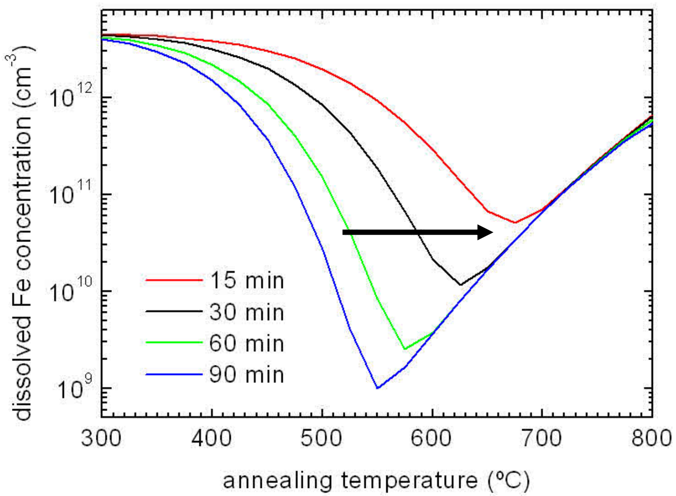
→ **Shorter process** requires **higher temperature**

→ Potentially several tenths percent efficiency increase for 15 min LTA

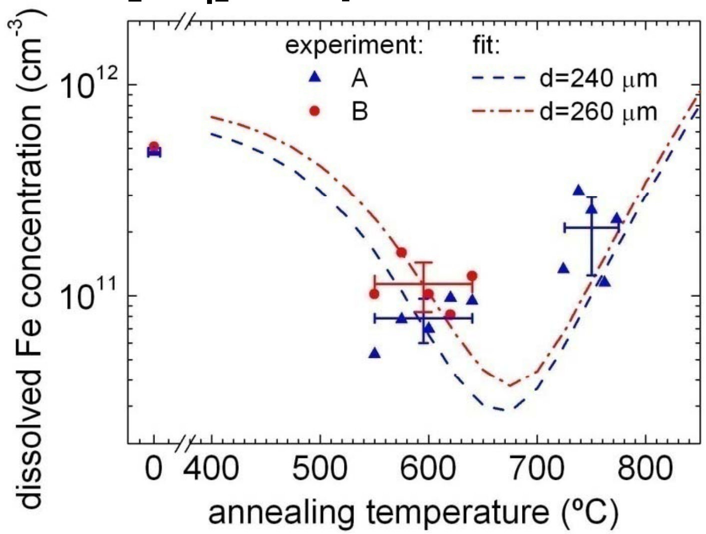


Hofstetter *et al.*, Physica status solidi c, accepted for publication (2010)

[Fe_i] - simulation



[Fe_i] - experimental



Centesil: research on solar silicon

CENTESIL
Centro de tecnología del silicio solar

Corporation formed in 2006 by two Universities and three companies

POLITÉCNICA

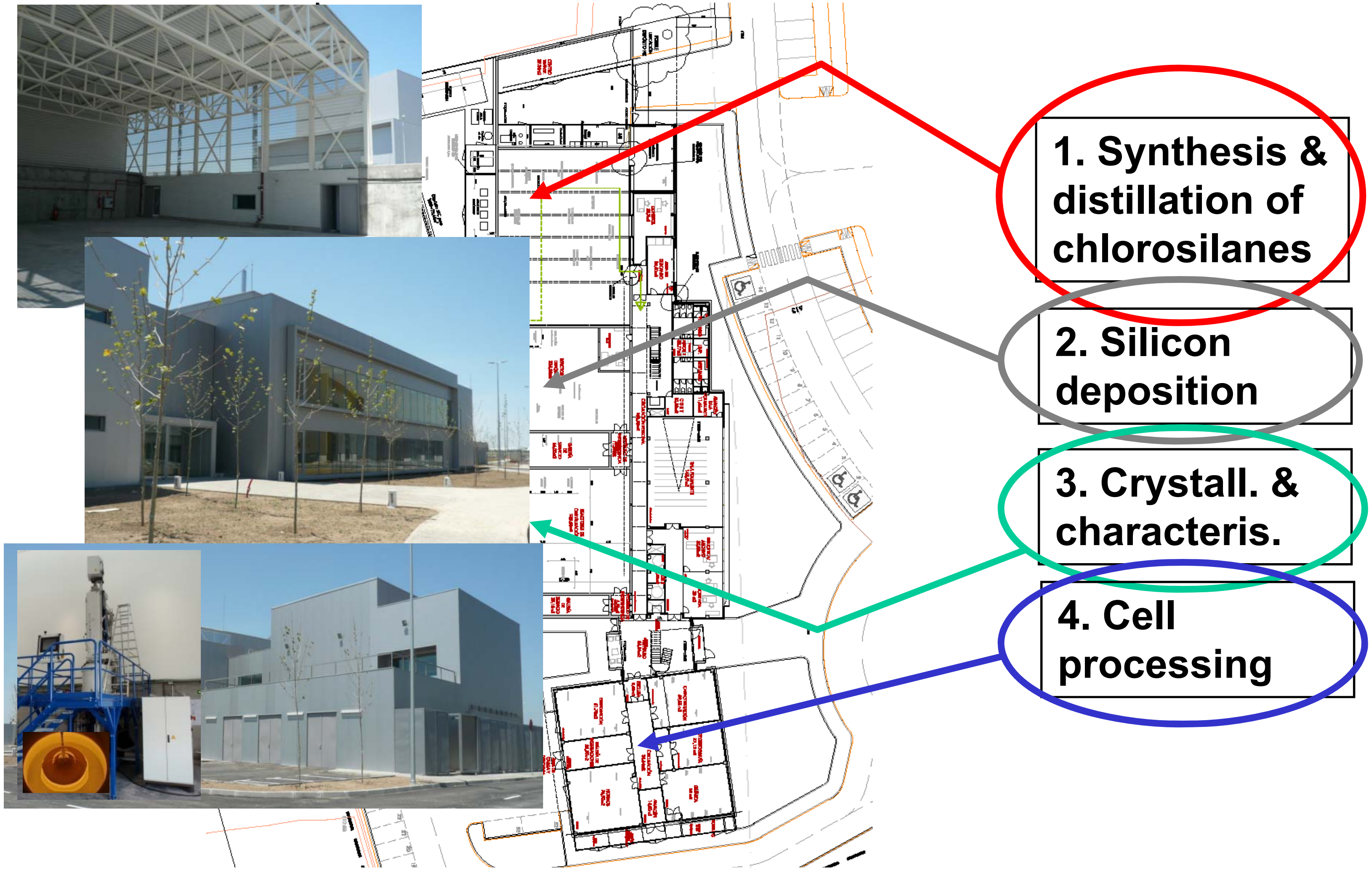
DC WAFERS

isofotón

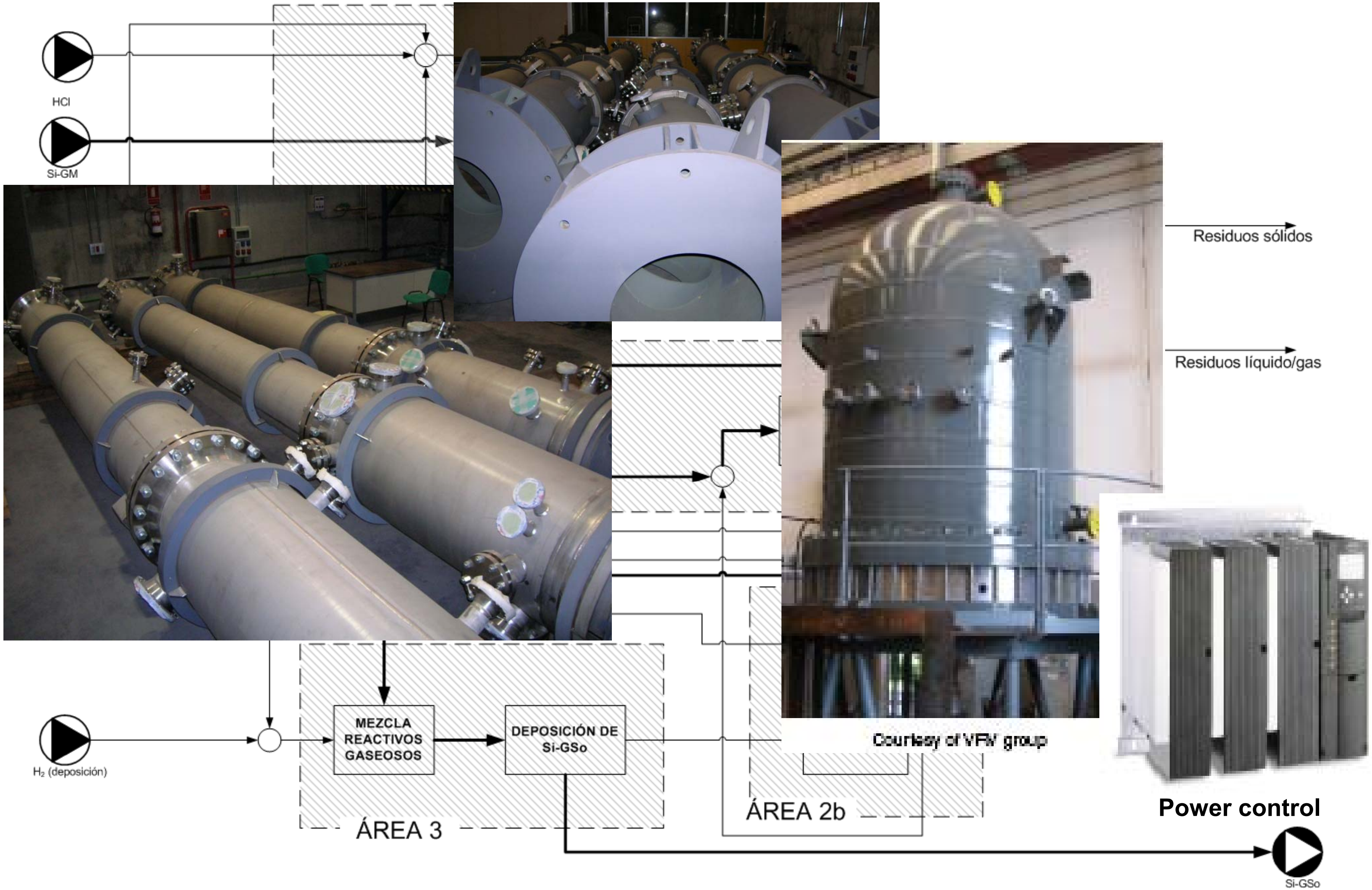
TECNICAS REUNIDAS

- ✓**Flexible tool for R&D on polysilicon**
- ✓**50 t/a poly pilot plant that follows the chlorosilane route**
- ✓**Value chain from feedstock to solar cell**

Technological areas in the pilot plant

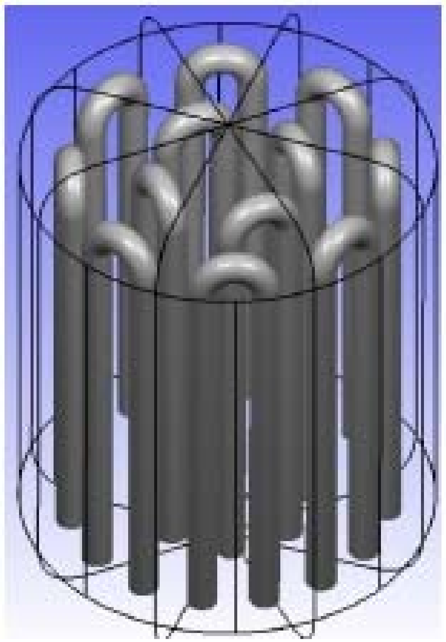


Process steps in Centesil's polysilicon pilot plant



Model for CVD deposition

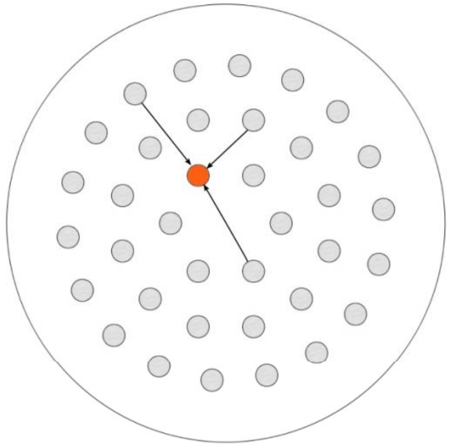
- The complex radiative exchange within the reactor is analysed:

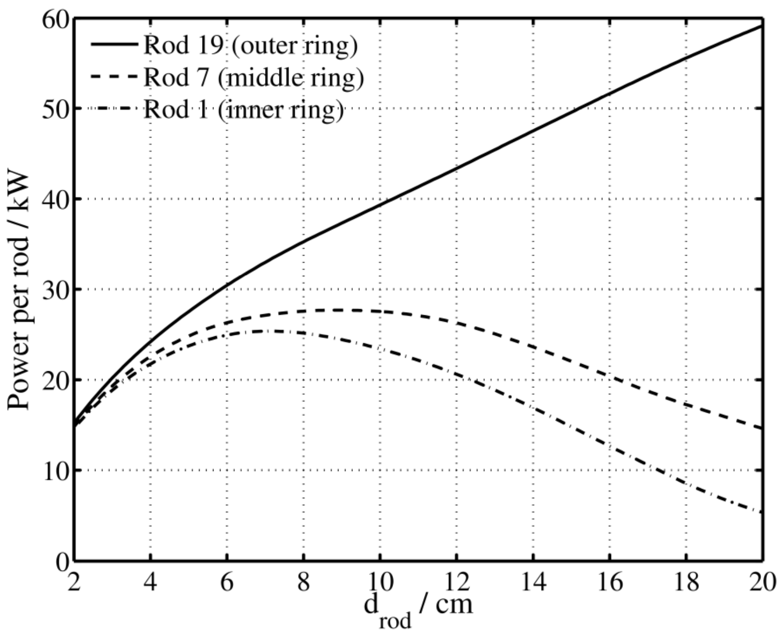


The radiation falls on the wall and on the other rods

The radiation is reflected by the wall and the other rods

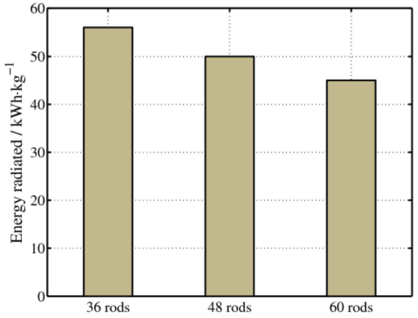
Radiation originated by the other rods





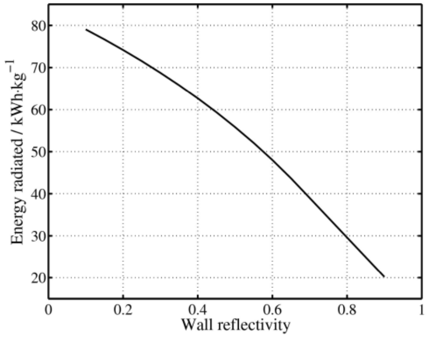
del Coso *et al.*, Solar Energy Materials and Solar Cells, accepted

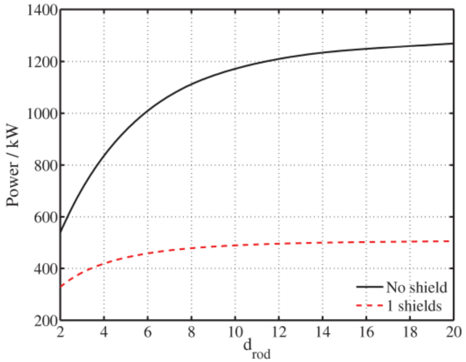
Reduction of radiation losses in the CVD reactor



☞Enlarging reactor capacity ⇒ ↓ 20% energy radiated

☞Enhancing wall reflectivity ⇒ ↓ 30% energy radiated





☞Using a thermal shield ⇒ ↓ 50% energy radiated…

☞… but thermal shield can reach >900ºC, producing contamination and silicon losses

☞Patent presented by CENTESIL to solve the problem

CENTESIL`s assets

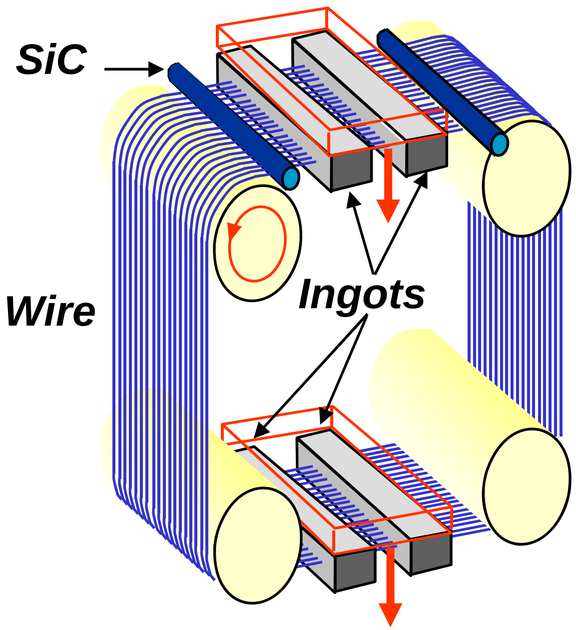
- ✓ The only independent research centre worldwide developing polysilicon at the pilot plant scale
- ✓ Know-how on polysilicon:
  - ✓ Lab prototypes of some relevant reactors for chlorosilanes
  - ✓ Conceptual and detailed design of an industrial polysilicon pilot plant
  - ✓ Cost estimates for investment and operation of an industrial plant
- ✓ Equipment and expertise for crystallisation, characterisation and cell processing

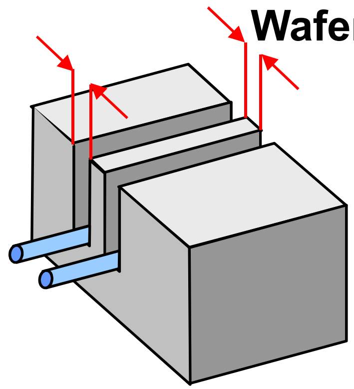
CENTESIL

Centro de tecnología del silicio solar

CENTESIL will be glad to incorporate new parters!!

Very thin wafers for solar cells

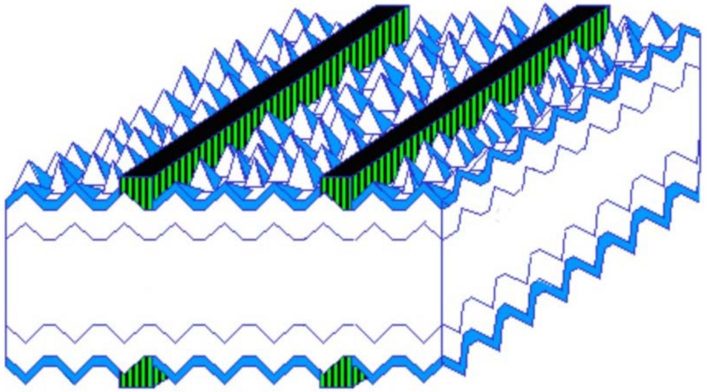


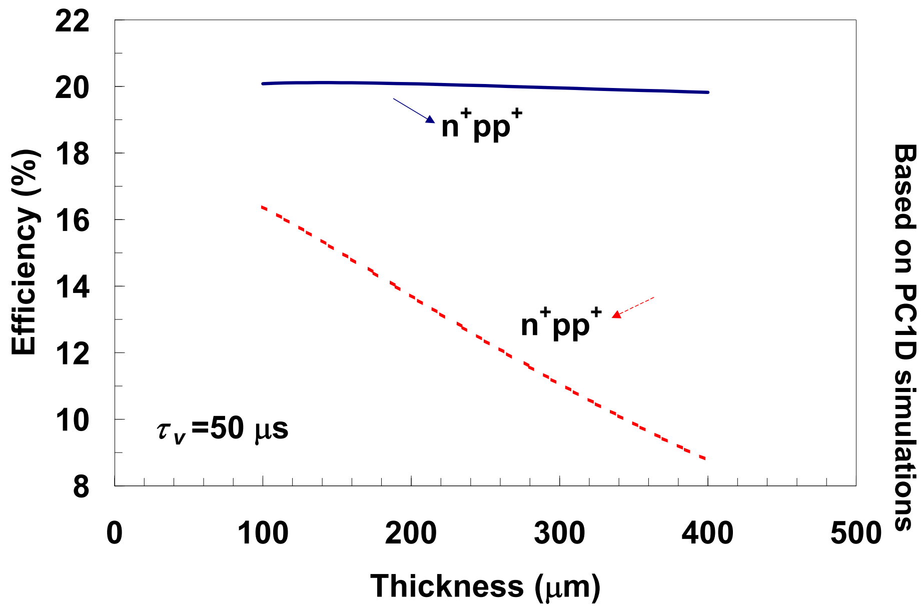


- Assessment for the automatic singulation of wafers thinner than 100 mm
- Study of the mechanical properties of silicon
- The concept of crack-free wafer, removing the cracks introduced at any processing step by an adequate chemical/thermal treatment.

Solar cells for very thin substrates

- **Bifacial structure, good candidate for very thin wafers**





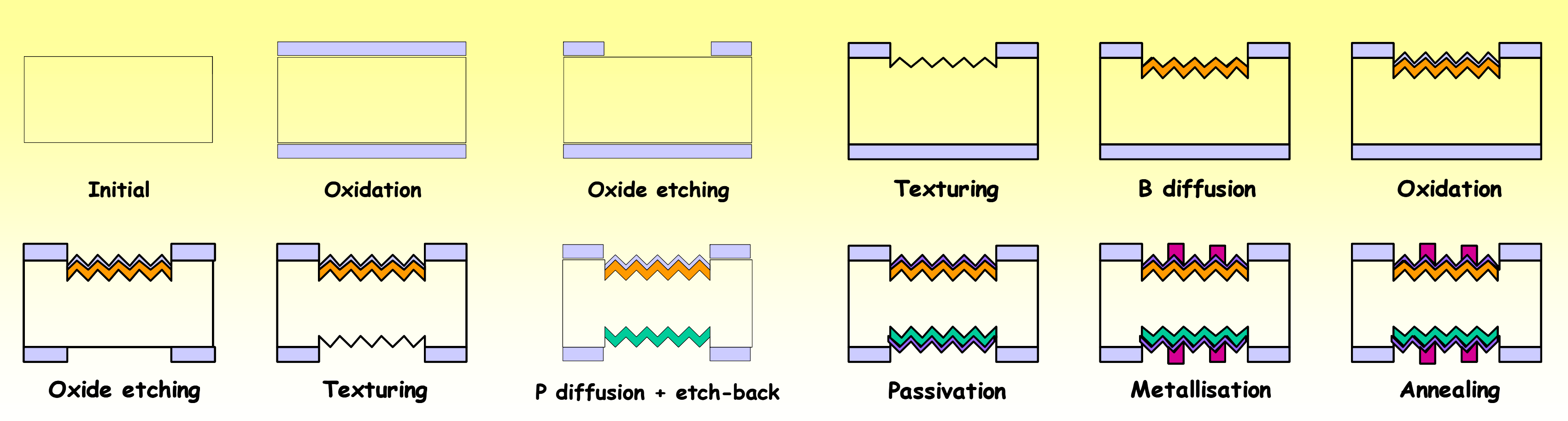
✓**It avoids the wafer bending**

✓**It has good light trapping properties**

✓**It has low recombination at the rear**

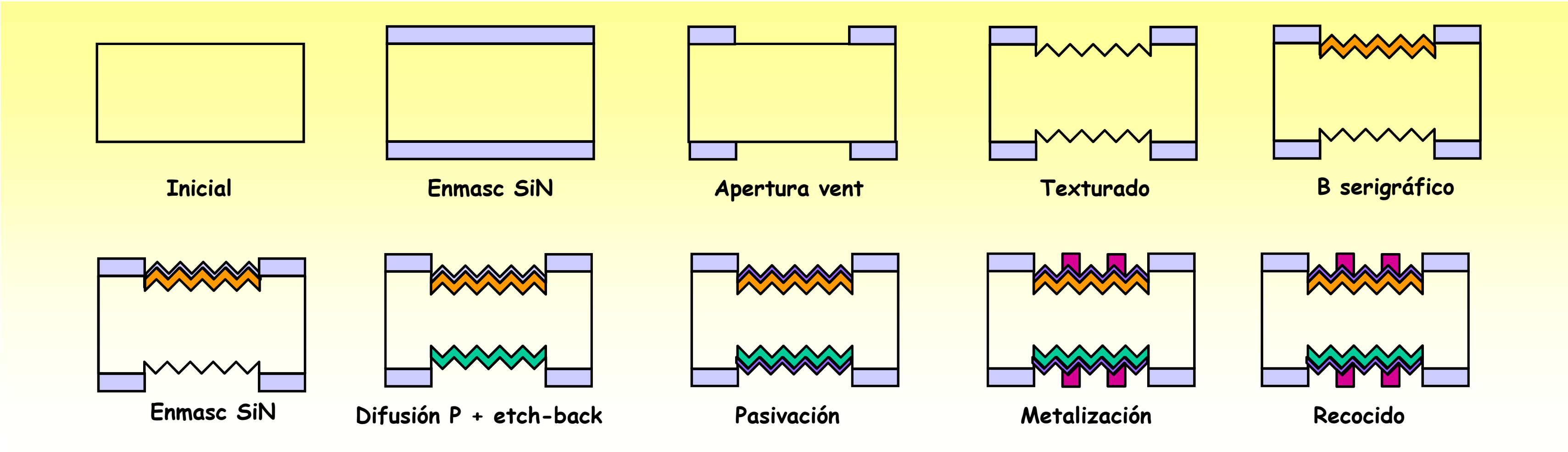
✓**Its bifacial use (in flat albedo modules) takes advantage of light impinging at the rear**

Thin Cz bifacial solar cells



	Cz 10 Ωcm, 140 μm		Cz 10 Ωcm, 220 μm	
Type / Illumination	n/p^+	n/n^+	p/p^+	p/n^+
J_{sc} (mA/cm^2)	31.6	36.3	30.0	35.0
V_{oc} (mV)	610	612	571	587
FF	0.772	0.764	0.762	0.779
Efficiency (%)	**14.9**	**17.0**	**13.0**	**16.0**

Bifacial solar cells with screenprinted B emitter

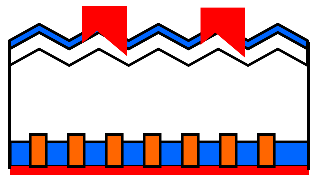


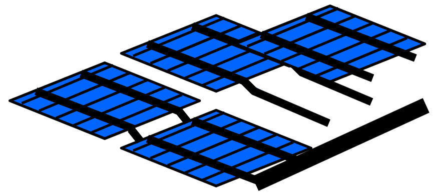
	FZ 10 Ωcm, 220 μm		Cz 7 Ωcm, 220 μm	
Type / Illumination	**n / p$^+$**	**n / n$^+$**	**n / p$^+$**	**n / n$^+$**
J_{sc} (mA/cm^2)	36.8	32.3	35.6	31.4
V_{oc} (mV)	613	609	598	597
FF	0.747	0.752	0.747	0.732
Efficiency(%)	**16.8**	**14.8**	**15.8**	**13.7**

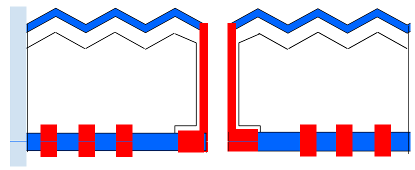
Advanced c-Si technologies

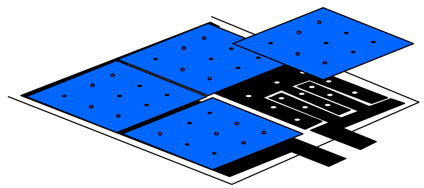
- **Different approaches are pursued at the scientific and industrial levels**

	Wafer	Cell & module concept	Encapsulated cell efficiency
Adv.Basepower (Reference)	mc-Si 180 µm	standard front to rear	15.8%
Multistar	mc-Si 120 µm	advanced front to rear	16.7%
MultistaR	mc-Si 120 µm	Metall Wrap-Through (MWT)	17.0%
Superslice	Cz-Si 120 µm	advanced front to rear	18.7%
SuperslicE	Cz-Si 120 µm	Emitter Wrap-Through (EWT)	18.5%
Ribbonchamp	ribbon Si 120 µm	Metall Wrap-Through (MWT)	16.0%
Epi.C	umg Si + epi 120 µm + 20 µm	advanced front & rear	16.0%









CrystalClear roadmap – short term

Conclusions

- **The Instituto de Energía Solar is willing to contribute to the deployment of Photovoltaics through R&D in materials, devices and systems**

- **Crystalline silicon technology is able to bring PV to competitiveness, provided a number of challenges are addressed through the whole value chain**

- **Spain is well positioned in the field of crystalline silicon technology, as it has relevant industrial and R&D experience in the whole value chain, from metallurgical silicon to PV installations**

POLITÉCNICA

Instituto de Energía Solar

IES:1979-2009

30 years developing PV